DFPD 94/TH/51

Implications of a Light Stop for the Spontanous CP Breaking at Finite Temperature in a Nonminimal Supersymmetric Model

D. Comelli[a,b,1], M. Pietroni[c,d,2] and A. Riotto[d,e,3]

[(a)] *Dipartimento di Fisica Teorica, Universita' di Trieste, 34014, Italy*

[(c)] *DESY Theory Group, Deutsches Elektronen-Synchroton*
Notkerstrasse 85, 22603 Hamburg, Germany

[(d)] *Istituto Nazionale di Fisica Nucleare,*
Sezione di Trieste, 34014 Trieste, Italy

[(c)] *Istituto Nazionale di Fisica Nucleare,*
Sezione di Padova, 35100 Padua, Italy

[(d)] *Instituto de Estructura de la Materia,CSIC,*
Serrano, 123, E-20006 Madrid, Spain

Abstract

We study the implications of a light stop for the spontaneous CP breaking at finite temperature in the Higgs sector of the Minimal Supersymmetric Standard Model with a gauge singlet. Assuming CP conservation at zero temperature, we show that the presence of a large mixing between the left- and the right-handed stops can trigger easily the spontaneous breaking of CP inside the bubbles nucleated during the electroweak phase transition. This allows to avoid the fine-tuning among the vacuum expectation values in the region of interest for the generation of the baryon asymmetry, namely the bubble walls, which has been recently analized.

[1]Email: comelli@mvxtst.ts.infn.it

[2] Email:pietroni@vxdesy.desy.de

[3]On leave of absence from International School for Advanced Studies (ISAS), Trieste, Italy; Email:riotto@tsmi19.sissa.it

The generation of the baryon asymmetry in the Universe (BAU) requires three basic ingredients [1]: baryonic violating interactions, departure from thermal equilibrium and C and CP violation. Anomalous electroweak processes are known to provide the source of B violation [2], whereas the departure from thermal equilibrium can occur if the electroweak phase transition (EWPT) is of the first order and proceeds via bubble nucleation. These considerations make the possibility of generating the BAU during the electroweak phase transition very appealing [3]. As far as the CP violation is concerned, it is still an open question if the necessary amount of CP violation to produce enough baryon asymmetry is present in the standard model [4].

In the minimal supersymmetric extension of the standard model (MSSM) [5] the requirement that explicit CP violating phases provide the necessary amount of CP violation necessary for the generation of the BAU gives rise to additional strong constraints on the parameter space of the model [6]. Spontaneous CP breaking (SCPB) in the Higgs sector can be triggered by radiative corrections [7] at zero temperature. Nevertheless, as predicted by Georgi and Pais [8], it requires the existence of a pseudoscalar Higgs boson with a mass of a few GeV [9], which has been ruled out by LEP [10]. When finite temperature effects are considered, even if SCPB in the MSSM during the EWPT can occur in a wide region of the parameter space [11, 12] it requires as a general tendency small values of the mass of the pseudoscalar Higgs boson, whereas recent results on the phase transition in the MSSM [13] seem to point towards the opposite direction in order not to wash out the generated baryon asymmetry.

Very recently, the question of SCPB at finite temperature in the MSSM with a gauge singlet, the so-called next-to-minimal supersymmetric standard model (NMSSM) [14], has been addressed [15] in the case of negligible left-right mixing in the stop sector. Assuming CP conservation at zero temperature and including the contributions to the one-loop effective potential both of the standard model particles and of the supersymmetric ones, it has been shown that SCPB in the broken phase (*i.e.* inside the bubbles nucleated during the EWPT) is prevented by two main reasons: large plasma effects in the Higgs sector and the great reduction at finite temperature of the large one-loop corrections coming from the top-stop sector at zero temperature when both the stops present in the spectrum are nearly degenerate (*i.e.* negligible left-right mixing) and with a mass of order of the critical

temperature [15]. Even if the SCPB can occur in the region of interest for the generation of the baryon asymmetry, namely in the bubble walls, this requires a fine-tuning among the values of the vacuum expectation values (VEV's) inside the walls which makes the phenomenon not very appealing.

In this Letter we argue that, in the framework of NMSSM, SCPB can easily occur inside the expanding bubbles thus avoiding any fine-tuning described in ref. [15][4] when a large left-right mixing in the stop sector is considered. Indeed, in this case, a relatively light stop $\tilde{t}_2$ appears in the spectrum and its presence can have many implications, for example as regards the ρ parameter, $K^0-\overline{K}^0$ mixing, the rare decay $b \to s+\gamma$ and the proton decay through dimension-5 operators in grand unified extension of the supersymmetric model [16]. Very recently the OPAL Collaboration has excluded the existence of a light stop with a mass below ~ 45 GeV unless a mixing angle $\theta_{\tilde{t}}$ between the left- and the right-handed partners is in the range $0.85 < \theta_{\tilde{t}} < 1.15$ and the mass difference between the $\tilde{t}_2$ and the lightest neutralino is smaller than 5 GeV [17]. From now on we shall take the conservative bound $m_{\tilde{t}_2} > 45$ GeV.

The superpotential involving the superfields $\hat{H}_1$, $\hat{H}_2$ and $\hat{N}$ in the NMSSM is

$$W = \lambda \hat{H}_1 \hat{H}_2 \hat{N} - \frac{1}{3} k \hat{N}^3 + h_t \hat{Q} \hat{H}_2 \hat{U}^c, \tag{1}$$

where the $\hat{N}^3$ term is present to avoid a global Peccei-Quinn $U(1)$ symmetry corresponding to $\hat{N} \to \hat{N} \mathrm{e}^{i\theta}$ and $\hat{H}_1 \hat{H}_2 \to \hat{H}_1 \hat{H}_2 \mathrm{e}^{-i\theta}$, and $\hat{Q}$ and $\hat{U}^c$ denote respectively the left-handed quark doublet and the (anti) right handed quark singlet of the third generation. The tree level potential is given by

$$\begin{aligned}
V_{tree} &= V_F + V_D + V_{soft}, \\
V_F &= |\lambda|^2 \left[|N|^2 \left(|H_1|^2 + |H_2|^2 \right) + |H_1 H_2|^2 \right] + |k|^2 |N|^4 \\
&- \left(\lambda k^* H_1 H_2 N^{*2} + \text{h.c.} \right), \\
V_D &= \frac{1}{8} \left(g^2 + g'^2 \right) \left(|H_1|^2 - |H_2|^2 \right)^2 + \frac{1}{2} g^2 \left| H_1^\dagger H_2 \right|^2, \\
V_{soft} &= m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + m_N^2 |N|^2 \\
&- \left(\lambda A_\lambda H_1 H_2 N + \text{h.c.} \right) - \left(\frac{1}{3} k A_k N^3 + \text{h.c.} \right),
\end{aligned} \tag{2}$$

[4]We remind the reader that the VEV's and the associated phases continously change from inside to outside the bubbles where they are vanishing so that nonvanishing phases will be present in the bubble walls.

where $H_1^T \equiv (H_1^0, H^-)$ and $H_2^T \equiv (H^+, H_2^0)$ and g and g' are the gauge couplings of $SU(2)_L$ and $U(1)_Y$, respectively. Redifining the global phases of H_2 and N, it can be shown that all the parameters in eq. (2) can be made real, except the ratio $r = A_\lambda / A$, $A_k \equiv A$. We assume this parameter to be real [18], *i.e.* no explicit CP violation in the potential of eq. (2).

If we define

$$\langle H_1^0 \rangle \equiv v_1 \, \mathrm{e}^{i\theta_1}, \quad \langle H_2^0 \rangle \equiv v_2 \, \mathrm{e}^{i\theta_2}, \quad \langle N \rangle \equiv x \, \mathrm{e}^{i\theta_3}, \tag{3}$$

and

$$3\theta_3 \equiv 2\varphi_3, \quad \theta_1 + \theta_2 + \theta_3 \equiv 2\varphi_1, \quad \theta_1 + \theta_2 - 2\theta_3 \equiv 2\varphi_1 - 2\varphi_3, \tag{4}$$

we can write the most general gauge invariant (under $SU(2)_L \otimes U(1)_Y$) potential in the vacuum

$$\begin{aligned} \langle V \rangle &= D_1 v_1^4 + D_2 v_2^4 + D_3 v_1^2 v_2^2 + D_4 v_2^2 x^2 + D_5 v_2^2 x^2 + D_6 x^4 \\ &+ D_7 v_1 v_2 x^2 \cos(2\varphi_1 - 2\varphi_3) + D_8 m_1^2 v_1^2 + D_9 m_2^2 v_2^2 + D_{10} m_N^2 x^2 \\ &+ D_{11} v_1 v_2 x \cos(2\varphi_1) + D_{12} x^3 \cos(2\varphi_3) \, . \end{aligned} \tag{5}$$

It has been shown by Romao [19] that the minimum of this potential at the tree level can never be CP breaking. On the other hand, when one-loop corrections at zero temperature from the top-stop sector are added, CP can be spontaneously broken [20]. However, the LEP upper bound limit on the mass of the lightest Higgs boson particle [21], $m_h > 60$ GeV, severly constrains the parameter space due to the general tendency of having two neutral and one charged Higgs boson with masses smaller than ~ 110 GeV when SCPB occurs. Moreover, the allowed area only exists for stops heavier than ~ 3 TeV, $\tan\beta = v_2/v_1 \simeq 1$ and $\lambda < 0.25$ [20]. In the following we shall assume that CP is conserved at zero temperature so that experimental constraints still allow large portions of the parameter space, in particular large values of $\tan\beta$ and λ.

The one-loop correction to the tree level potential at zero temperature in the $\overline{DR}$ scheme of renormalization reads

$$V_1^0 = \frac{1}{64\pi^2} \mathrm{Str} \left\{ \mathcal{M}^4(\phi) \left[\ln \frac{\mathcal{M}^2(\phi)}{Q^2} - \frac{3}{2} \right] \right\}, \tag{6}$$

where $\mathcal{M}^2(\phi)$, with $\phi \equiv (H_1^0, H_2^0, N)$, is the field dependent squared mass matrix, the supertrace Str properly counts the degree of freedom, Q is the renormalization point and

the Q dependence in eq. (6) is compensated by that of the renormalized parameters, so that the full effective potential is independent of Q up to the next-to-leading order.

The stop squared mass matrix in the basis $(\tilde{t}_L, \tilde{t}_R)$ is given by

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} m^2_{LL} & m^2_{LR} \\ m^{*2}_{LR} & m^2_{RR} \end{pmatrix}, \tag{7}$$

where

$$\begin{aligned} m^2_{LL} &= \tilde{m}^2_q + h_t^2 \left|H_2^0\right|^2 + \left(\frac{g^2}{12} - \frac{g'^2}{4}\right)\left(\left|H_2^0\right|^2 - \left|H_1^0\right|^2\right), \\ m^2_{RR} &= \tilde{m}^2_u + h_t^2 \left|H_2^0\right|^2 - \frac{g'^2}{3}\left(\left|H_2^0\right|^2 - \left|H_1^0\right|^2\right), \\ M^2_{LR} &= h_t \left(A_t H_2^0 + \lambda N^* H_1^{*0}\right). \end{aligned} \tag{8}$$

Here A_t is the soft trilinear term associated to the $\hat{Q}\hat{H}_2\hat{U}^c$ term in the superpotential. The mass matrix is easily diagonalized by writing the sfermion stop eigenstates as

$$\begin{aligned} \tilde{t}_1 &= -\tilde{t}_L \sin\theta_{\tilde{t}} + \tilde{t}_R \cos\theta_{\tilde{t}}, \\ \tilde{t}_2 &= \tilde{t}_L \cos\theta_{\tilde{t}} + \tilde{t}_R \sin\theta_{\tilde{t}}, \end{aligned} \tag{9}$$

whose mass eigenvalues are

$$m^2_{\tilde{t}_1,\tilde{t}_2} = \frac{1}{2}\left[\left(m^2_{LL} + m^2_{RR}\right) \pm \sqrt{\left(m^2_{LL} - m^2_{RR}\right)^2 + 4\left|m^2_{LR}\right|^2}\right]. \tag{10}$$

For large values of A_t, $m_{\tilde{t}_2} \ll m_{\tilde{t}_1}$ and $\tilde{t}_2$ can be very light. Note, however, that A_t is bounded from above to avoid dangerous color breaking minima [22], $A_t^2 < 3\left(\tilde{m}^2_q + \tilde{m}^2_u + m^2_2\right)$.

The one-loop correction to the tree level potential at finite temperature reads [23]

$$\begin{aligned} V_1^T &= \frac{T^4}{2\pi^2} \mathrm{Str}\, J\left[\frac{\mathcal{M}^2(\phi)}{T^2}\right] + \Delta V_{daisy}, \\ \Delta V_{daisy} &= \frac{T}{12\pi} \sum_{i,bos} n_{i,bos}\left[\left(m_{i,bos}(\phi)^2 + \Pi_{i,bos}\right)^{3/2} - m_{i,bos}(\phi)^3\right], \\ J_{bos,fer}(y^2) &= \int_0^\infty dx\, x^2 \log\left(1 \mp \mathrm{e}^{-\sqrt{x^2+y^2}}\right). \end{aligned} \tag{11}$$

Here the $\Pi_{i,bos}$ denotes the thermal polarization mass for each boson with degrees of freedom $n_{i,bos}$ contributing to the Debye mass [24].

Defining the new parameters

$$
\begin{aligned}
B_4 &= \frac{D_1+D_2}{4} - \frac{1}{4}D_3 + \frac{1}{8}\frac{D_7 D_{11}}{D_{12}}, \\
B_5 &= \frac{D_1+D_2}{4} + \frac{1}{4}D_3 - \frac{1}{8}\frac{D_7 D_{11}}{D_{12}}, \\
B_6 &= \frac{D_1-D_2}{2}, \\
B_7 &= \frac{D_4-D_5}{2}, \\
B_8 &= \frac{D_4+D_5}{2}, \\
B_9 &= D_6 - \frac{1}{2}\frac{D_7 D_{12}}{D_{11}},
\end{aligned} \tag{12}
$$

whose tree level values can be inferred from eqs. (2) and (5) [15], it is easy to show that CP can be spontanously broken only if the following system of conditions is satisfied

$$
\frac{D_{11}D_7}{D_{12}} > 0 \ \text{ plus } \left\{ \begin{array}{c} B_9 > 0, \\ B_5 > 0, \\ 4B_5B_9 - B_8^2 > 0, \end{array} \right. , \tag{13}
$$

which, at the tree level, does not have any solutions in the r space. The key point is the following: whenever the condition $D_{11}D_7/D_{12} > 0$ ($\Rightarrow r < -1/3$) assuring that the nonvanishing phases in eq. (5) correspond to a minimum, then the condition $B_5 > 0$ ($\Rightarrow r > -1/3$) is never satisfied at the tree level. When one-loop corrections are considered, among the B parameters, it is just B_5 which receives the largest contributions from the top-stop sector and from the Higgs sector (at finite temperature). It is then clear that the corrections to the tree level potential should drive B_5 to positive values (for $r < -1/3$) to have SCPB.

A complete analysis on how to calculate the corrections to the tree level coefficients of the most general potential, eq. (5), is given in the Appendix of ref. [15].

After having made use of the minimizations equations at zero temperaure to express the m_1^2, m_2^2 and m_N^2 masses in terms of the other parameters of the potential, we define the critical temperature T_c as the value of T at which the origin of the field space becomes a saddle point [15] which happens when one of the $\overline{m}_i = m_i^2 + \Pi_i$ ($i = 1, 2, N$) vanishes. The first of the m_i^2's to run to negative values through the renormalization group equations is expected to be m_2^2 as a consequence of large values of the top Yukawa coupling. As a consequence, the EWPT is expected to occur mostly along the H_2^0 direction [25].

When large left-right mixing in the stop sector is present, the heaviest stop $\tilde{t}_1$ contribution to V_1^T is suppressed since $m_{\tilde{t}_1}$ is much larger than T and the values of $\overline{m}_2^2$ is

$$\overline{m}_2^2 = m_2^2 + \frac{1}{8}\left(3g^2 + g'^2 + \frac{4}{3}\lambda^2 + 4h_t^2\right) T^2. \tag{14}$$

In Fig. 1 we have fixed the critical temperature T_c = 150 GeV and shown the curve corresponding to $\overline{m}_2^2(T_c) = 0$. The points in the plane $(\lambda, m_{\tilde{t}_2})$ lying on the curve are then the points for which T_c =150 GeV. Indeed, since the EWPT is known to be of the first order, it occurs when $\overline{m}_2^2$ is still positive, *i.e* at temperatures higher than T_c: since all the points in the $(\lambda, m_{\tilde{t}_2})$ plane below the solid curve correspond to $\overline{m}_2^2 > 0$, they correspond the region of the parameter space where the EWPT occurs at temperatures smaller than or equal to 150 GeV.

After having calculated the corrections to the D and B parameters at finite temperature with the method described in ref. [15] (we have included all the standard model particles as well as stops, charginos, neutralinos, charged and neutral Higgs bosons), we have imposed SCPB to occur inside the bubbles in the broken phase, *i.e.* the satisfaction of the system in eq. (13). The results are shown in Figs 1 and 2 for different values of the parameters.

In Fig. 1 the allowed region lies under the solid line, roughly for $\lambda < 0.45$. In Fig. 2 we have chosen $\tan\beta = 1.2$ and SCPB can occur for $\lambda < 0.6$. Moreover, the lightest pseudoscalar A^0 should be heavier than $\sim$ 20 GeV [10] and the dashed line corresponds to $m_{A^0} = 40$ GeV. The lightest CP even particle h has not been produced in the decay $Z^0 \rightarrow Z^{*0} + h$ corresponding to the conservative bound $m_h > 60$ GeV [21]. These constraints impose that λ must lie in the range $0.1 < \lambda < 0.5$. We have also checked that in the allowed regions the theory remais perturbative in the sense that the perturbation expansion parameter $\beta \sim g^2(T/2\pi\, \overline{m}_2)$ remains smaller than 1 [24].

Much of the behaviour described above can be understood fairly well analytically when considering the largest one-loop corrections acting mainly on B_5, *i.e* those proportional to the top Yukawa coupling and those coming the Higgs sector. As we said above, for large A_t the heaviest stop $\tilde{t}_1$ contributes only to V_1^0 so that its correction to B_5 reads

$$\begin{aligned}(\Delta B_5)_{\tilde{t}_1} &= \frac{(\Delta D_2)_{\tilde{t}_1}}{4} = \frac{1}{4}\left[\frac{6}{64\pi^2}\, h_t^4 \ln\frac{m_{\tilde{t}_2}^2}{\overline{Q}^2}\right. \\ &+ \left.\frac{6}{64\pi^2}\, h_t^4 \left(\frac{A_t^2}{\tilde{m}^2} - \frac{A_t^4}{12\,\tilde{m}^4}\right)\right], \end{aligned} \tag{15}$$

where we have assumed $\tilde{m}_q = \tilde{m}_u = \tilde{m}$ and neglected the gauge couplings. $\overline{Q}$ has been properly so that the contribution of $\tilde{t}_1$ to the minimization conditions is suppressed.

When the corrections to B_5 from the top and lightest stop $\tilde{t}_2$ are added, the overall *positive* correction $(\Delta B_5)_t$ from the top-stop sector is given by

$$\begin{aligned}(\Delta B_5)_t &= \frac{(\Delta D_2)_t}{4} = \frac{1}{4}\left[\frac{6}{64\pi^2}\, h_t^4 \ln\frac{m_{\tilde{t}_2}^2}{A_f\, T^2} + \frac{6}{64\pi^2}\, h_t^4 \left(\frac{A_t^2}{\tilde{m}^2} - \frac{A_t^4}{12\, \tilde{m}^4}\right)\right. \\ &+ \left.\frac{6}{64\pi^2}\, h_t^4 \ln\frac{A_b}{A_f}\right], \end{aligned} \tag{16}$$

where $A_b = 16\, A_f = 16\, \pi^2(3/2 - 2\gamma_E)$, γ_E being the Euler constant.

As noted in ref. [15], the Higgs sector gives the largest *negative* contribution to B_5

$$(\Delta B_5)_h = -\frac{1}{8\pi}\frac{T}{\overline{m}_2}\frac{1}{16}\left(\frac{25}{4}g^4 + \frac{30}{4}g'^4 - \frac{19}{2}g^2 g'^2\right). \tag{17}$$

Imposing now that $B_5 = (B_5)_{tree} + (\Delta B_5)_t + (\Delta B_5)_h > 0$ we find

$$\lambda^2 < 4\, \frac{(\Delta B_5)_t + (\Delta B_5)_h}{|1 + 3r|}, \tag{18}$$

which explains the upper bound on λ to have SCPB inside the bubble walls.

Here we want to make some comments. In ref. [15] the case $A_t \simeq 0$ and thus two nearly degenerate in mass stops were considered. Moreover it was assumed that $m_{\tilde{t}_1} \simeq m_{\tilde{t}_2} \simeq T$ so that both stops contribute to V_1^T. In such a case it is not hard to see that the contribution to B_5 from the top-stop sector is considerably reduced and turns out to be proportional only to $h_t^4 \ln(A_b/A_f)$. As a consequence, the largest one-loop contribution to B_5 comes from the Higgs sector and, being the latter negative, no SCPB inside the bubbles is allowed. In this case the only possibility is the breaking of CP inside the bubble walls, which requires some fine-tuning among the VEV's in the walls [15]. Here we have shown that, when large left-right mixing in the stop sector is considered, SCPB can easily occur inside the bubbles. CP violating phases are then *automatically* present in the bubble walls (where, due to the strength of the transition, several baryogenesis mechanisms are expected to work [3]) . We also stress that SCPB is purely driven by plasma effects at finite temperature. Once the temperature falls down after the end of the EWPT, the plasma corrections to the effective potential become more and more suppressed and the CP conserving minimum is reached. This allows to avoid a very light spectrum in the Higgs

sector which is an inevitable prediction of the Georgi Pais theorem whenever a discrete symmetry is radiatively broken at zero temperature. Moreover, the light stop scenario can have several intriguing experimental consequences which could show up in the next generation of accelerators.

References

[1] A.D. Sakharov, Pis'ma Zh. Eksp. Fiz. **5** (1967) 32; JETP Lett. **5** (1967) 24.

[2] V.A. Kuzmin, V.A. Rubakov and M.E. Shaposhnikov, Phys. Lett. **B155** (1985) 36.

[3] For a review and exhaustive reference lists see A.D. Dolgov, Phys. Rep. **222** (1992) 309; A.G. Cohen, D.B. Kaplan and A.E. Nelson, Ann. Rev. Nucl. Part. Sci. **43** (1993) 27.

[4] G. Farrar and M.S. Shaposhnikov, Phis. Rev. Lett. **70** (1993) 2883 + (E) **71** (1993) 210; CERN-TH 6734/93 preprint; M.B. Gavela, P. Hernández, J. Orloff and O. Pène, CERN-TH 7089/93 preprint; P. Huet and E. Sather, SLAC preprint (1993) Hepph 9404302.

[5] For a review, see, for instance, H.E. Haber and G.L. Kane, Phys. Rep. **117** (1985) 77.

[6] A.G. Cohen and A.E. Nelson, Phys. Lett. **B297** (1992) 111.

[7] N. Maekawa, Phys. Lett. **B282** (1992) 387.

[8] H. Georgi and A. Pais, Phys. Rev. **D10** 1246. 1974

[9] A. Pomarol, Phys. Lett. **B287** (1992) 331.

[10] See, *e.g.*, J.F. Grivaz, in *Ten Years of SUSY Confronting experiments*, CERN-TH 6707/92 and PPE/92-180 preprint.

[11] D. Comelli and M. Pietroni, Phys. Lett. **B306** (1993) 67; J.R. Espinosa, J.M. Moreno and M. Quirós, Phys. Lett. **B319** (1993) 505.

[12] D. Comelli, M. Pietroni and A. Riotto, Nucl. Phys. **B412** (1994) 441.

[13] J.R. Espinosa, M. Quirós and F. Zwirner, Phys. Lett. **307** (1993) 106; A. Brignole, J.R. Espinosa, M. Quirós and F. Zwirner, Phys. Lett. **324** (1994)181.

[14] H. Nilles, M. Srednicki and D. Wyler, Phys. Lett. **B120** (1983) 346; J.P. Derendinger and C. Savoy, Nucl. Phys. **B237** (1984) 307; J. Gunion and H.E. Haber, Nucl. Phys.

B272 (1986) 1; J. Ellis, J. Gunion, H.E. Haber, L. Roskowski and F. Zwirner, Phys. Rev. **D39** (1989) 844; M. Drees, Int. J. Mod. Phys. **A4** (1989) 3635; L. Durand and J. Lopez, Phys. Lett. **B217** (1989) 463; P. Binetruy and C. Savoy, Phys. Lett. **B277** (1992) 453; J.R. Espinosa and M. Quirós, Phys. Lett. **B279** (1992) 92; T. Moroi and T. Okada, Phys. Lett. **B295** (1992) 73; U. Ellwanger and M. Rausch de Traunbenberg, Z. Phys. **C53** (1992) 521; U. Ellwanger, Phys. Lett. **B303** (1993) 271; T. Elliot, S.F. King and P.L. White, Phys. Lett. **B305** (1993) 71; D. Comelli, UTS-DFT-92-30 preprint (1992); G. Kane, C. Kolda and J. Wells, Phys. Rev. Lett. **70** (1993) 2686; U. Ellwanger, M. Rausch de Traunberberg and C.A. Savoy, Phys. Lett. **315** (1993) 331; T. Elliot, S.F. King and P.L. White, Phys. Rev. **D49** (1994) 2435;

[15] D. Comelli, M. Pietroni and A. Riotto, DFDP 94/TH/82 and SISSA 94/81-A preprints, to be published in Phys. Rev. **D**.

[16] J. Ellis and S. Rudaz, Phys. Lett. **B128** (1983) 248; G. Altarelli and R. Ruckl, Phys. Lett. **B144** (1984) 126; I. Bigi and S. Rudaz, Phys. lett. **B153** (1985) 335; K. Hikasa and M. Kobayashi, Phys. Rev. **D36** (1987) 724; H. Baer and X. Tata, Phys. Lett. **B167** (1986) 241; M. Drees and K. Hikasa, Phys. Lett. **B252** (1990) 127; H. Baer, M. Drees, J. Gunion, R. Godbole and X. Tata, Phys. Rev. **D44** (1991) 725; T. Kon and T. Nonaka, Phys. Lett. **B319** (1993) 355; preprint ITP-SU-94/02 (hep-ph/9404230) and ITP-SU-94/03 (hep-ph/9405327); M. Fukugita, H. Murayama, M. Yamaguchi and T. Yanagida, Phys. Rev. Lett. **72** (1994) 3009; H. Baer, J. Sender and X. Tata, FSU-HEP-940430 (April 1994, hep-ph/9404342); J.L. Lopez, D.V. Nanopoulos and A. Zichichi, CERN-TH.7296/94 preprint; K.A. Olive and S. Rudaz, UMN-TH-1309/94 preprint;

[17] OPAl Collaboration, CERN-PPE/94-103 preprint.

[18] F. Del Alguila *et al.*, Phys. Lett. **B129** (1983) 77.

[19] J. Romao, Phys. Lett. **B173** (1986) 309.

[20] K.S. Babu and S.M. Barr, Phys. Rev. **D49** (1994) R2156.

[21] See, *e.g.*, G. Coingnet, talk given at the *XVI International Symposium on Lepton-Photon Interactions*, Cornell Univ., Ithaca, New York, 19-15 August 1993, to appear in the Proceedings.

[22] J.M. Frere, D.T.R. Jones and S. Raby, Nucl. Phys. **B222**, (1983) 11; C. Kounnas, A.B. Lahanas, D.V. Nanopuolos and M. Quirós, Nucl. Phys. **B236** (1984) 438; J.F. Derendiger and C.A. Savoy, Nucl. Phys. **B237** (1984) 307; J.A. Casas, A. Lleyda and C. Munoz, to appear.

[23] L. Dolan and R. Jackiw, Phys. Rev. **D9** (1974) 3320; S. Weinberg, Phys. Rev. **D9** (1974) 3357; D.J. Gross, R.D. Pisarski and L.G. Yaffe, Rev. Mod. Phys. **53** (1988) 43.

[24] See, *e.g.*, M. Quirós, IEM-09-71-93 preprint, based on the talk given at *4th Hellenic School on Elementary Particle Physics*, Corfu', Greece, 2-20 September (1993).

[25] M. Pietroni, Nucl. Phys. **B402** (1993) 27.

Figure Caption

Fig. 1) The allowed region for having SCPB in the plane $(\lambda, m_{\tilde{t}_2})$ lies under the solid line. Here $\tilde{m} = 400$ GeV, $A = 50$ GeV, $x = 250$ GeV, $T = 150$ GeV, $m_t = 174$ GeV, $r = -1.2$, $\tan\beta = 10$ and $k = 0.6$. The curve $\overline{m}_2 = 0$ is also indicated.

Fig. 2) The allowed region for having SCPB in the plane $(\lambda, m_{\tilde{t}_2})$ lies under the solid line. Here $\tilde{m} = 400$ GeV, $A = 50$ GeV, $x = 250$ GeV, $T = 150$ GeV, $m_t = 174$ GeV, $r = -0.8$, $\tan\beta = 1.2$ and $k = 0.5$. The curves $m_A = 40$ GeV and $m_h = 60$ GeV are also indicated.